Simberian
Electromagnetic Solutions

Measurement-assisted extraction of PCB interconnect model parameters with fabrication variations

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Outline

- Introduction
- Test coupon design and measurements
- Cross-sectioning and geometry variations
- Material models
- Material models identification & results
- Conclusion

Design of predictable PCB interconnects for 56 Gbps PAM-4 links…

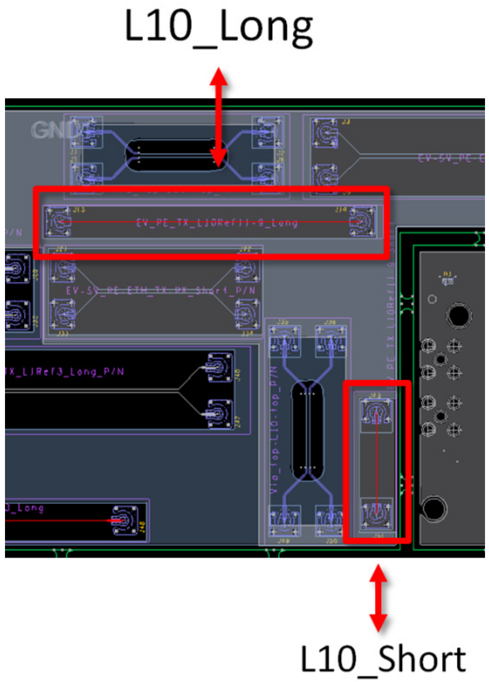
- Requires analysis to measurement correlation from 1-10 MHz up to at least 40-50 GHz
- Three necessary conditions to achieve such correlation *(1)*:
  - We need to know the actual PCB interconnect geometry
  - Broadband dielectric and conductor roughness models are needed
  - Accuracy of the analysis software and measurement equipment must be systematically validated for this bandwidth
- If all three conditions are satisfied, the models should correlate with the measurements
- The manufacturing variations may prevent such correlation ☹
- Statistical models are needed – this is an attempt to build such models

(1) M. Marin, Y. Shlepnev, Systematic approach to PCB interconnects analysis to measurement validation, 2018 IEEE Symp. on Electromagnetic Compatibility, Signal and Power Integrity, 2018.

TEST COUPON DESIGN AND MEASUREMENTS

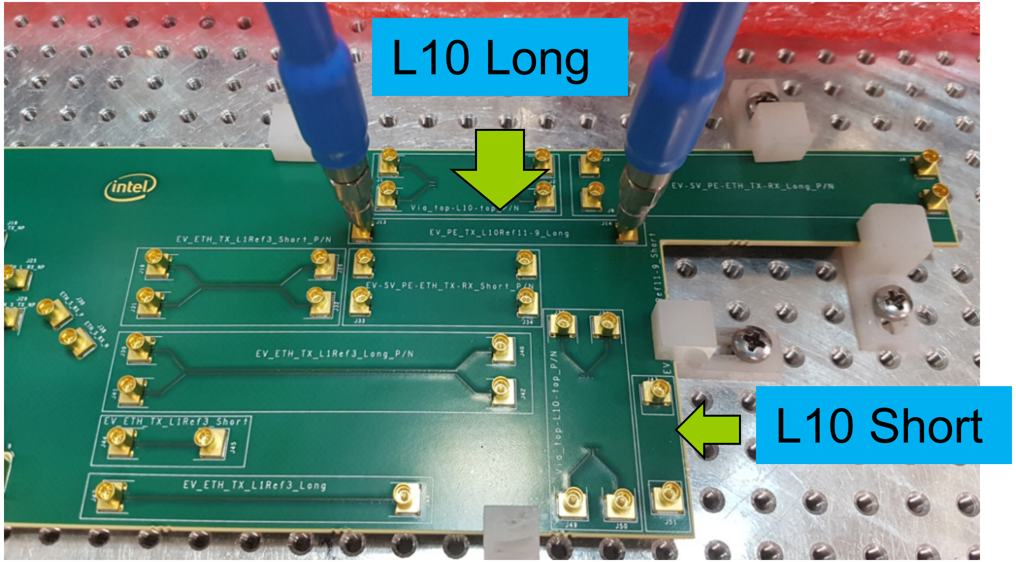
Coupon design

- Short and long segments of striplines with length difference 1.5 inch were placed on coupons (for extraction of GMS-parameters or Gamma)
- Megtron 7 and smooth HVLP copper were used, to meet 56 Gbps channel performance requirements
- Two adaptors from the snap-on MMPX connectors to 1.85f and to 2.92m are used for each structure
- Three batches of the same board were manufactured with some modifications of the launches
  - 5 boards were manufactured in the first batch (Rev1)
  - 20 boards in the second batch (Rev2)
  - 30 in the third batch (Rev3)



Measurements

- Network Analyser with 67 GHz bandwidth
- Mechanical Standard Calibration Kit



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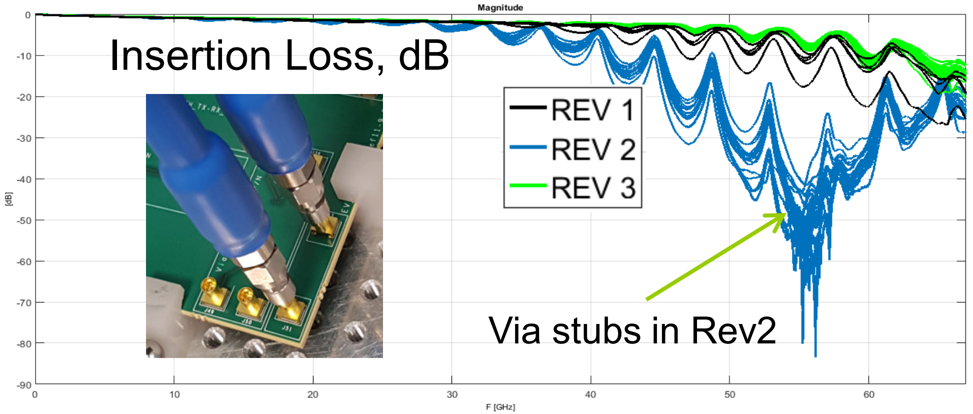
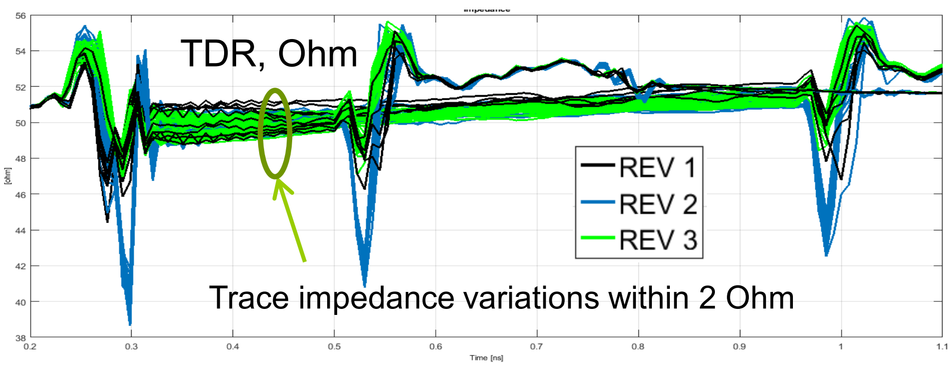
Measurements results

Excellent quality metrics (IEEE P370)

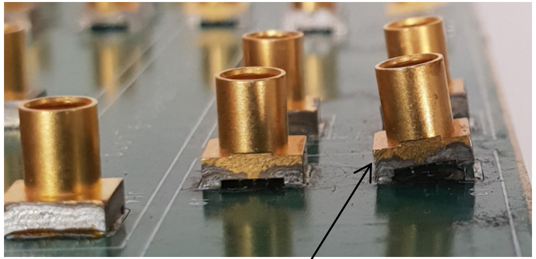
File name	Quality	Passivity	Reciprocity	Causality
C:\Repository\Simbeor\Support\Intel\Oct2_2018_DesignCon2019\Measure...				
BC001_L10_Short_Rev2.s2p	99	99.9	99.6	-
BC002_L10_Short_Rev2.s2p	98.9	99.9	99.6	-
BC003_L10_Short_Rev2.s2p	94	99.9	99.5	-
BC004_L10_Short_Rev2.s2p	98.9	99.9	99.6	-
BC005_L10_Short_Rev2.s2p	98.9	99.9	99.5	-
BC006_L10_Short_Rev2.s2p	98.8	99.9	99.5	-
BC007_L10_Short_Rev2.s2p	98.4	99.9	99.5	-
BC008_L10_Short_Rev2.s2p	99	99.9	99.6	-
BC009_L10_Short_Rev2.s2p	98.5	99.9	99.6	-
BC010_L10_Short_Rev2.s2p	98.9	99.9	99.5	-
BC011_L10_Short_Rev2.s2p	98.9	99.9	99.5	-
BC012_L10_Short_Rev2.s2p	99.1	99.9	99.6	-
BC013_L10_Short_Rev2.s2p	98.7	99.9	99.5	-
BC014_L10_Short_Rev2.s2p	98.6	99.9	99.5	-
BC015_L10_Short_Rev2.s2p	98.3	99.9	98.6	-
BC016_L10_Short_Rev2.s2p	98.9	99.9	99.5	-
BC017_L10_Short_Rev2.s2p	99	99.9	99.5	-
BC018_L10_Short_Rev2.s2p	99.1	99.9	99.4	-
BC019_L10_Short_Rev2.s2p	99	99.9	99.4	-
BC020_L10_Short_Rev2.s2p	98.6	99.9	99.3	-
BC021_L10_Short_Rev3.s2p	99.1	99.9	98.6	-
BC022_L10_Short_Rev3.s2p	99.1	99.9	99.2	-
BC023_L10_Short_Rev3.s2p	99.2	99.9	99	-
BC024_L10_Short_Rev3.s2p	99	99.9	98.9	-
BC025_L10_Short_Rev3.s2p	98.9	99.9	99.1	-
BC026_L10_Short_Rev3.s2p	98.9	99.9	98.9	-

Rev3 looks like the best for the identification

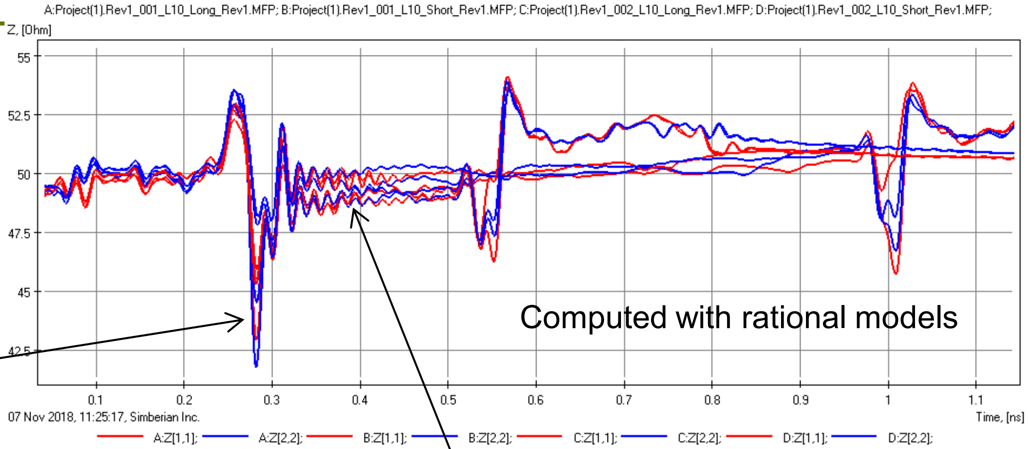




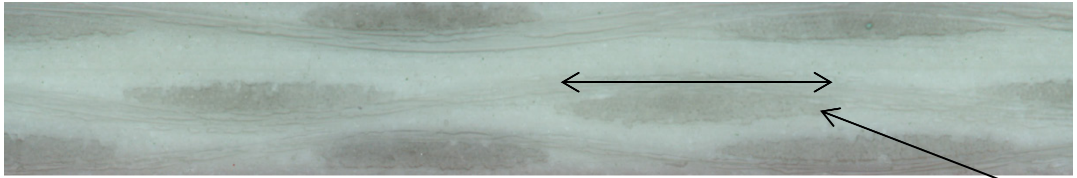
TDR close-up for Rev1

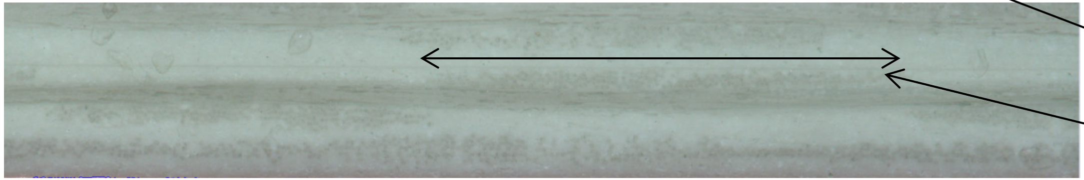


Over 5 Ohm impedance variations in connector to launch transition areas



About 1 Ohm impedance offset observed between short and long due to the orthogonal orientation of segments (FWE)





Fiber along short line (bunched)

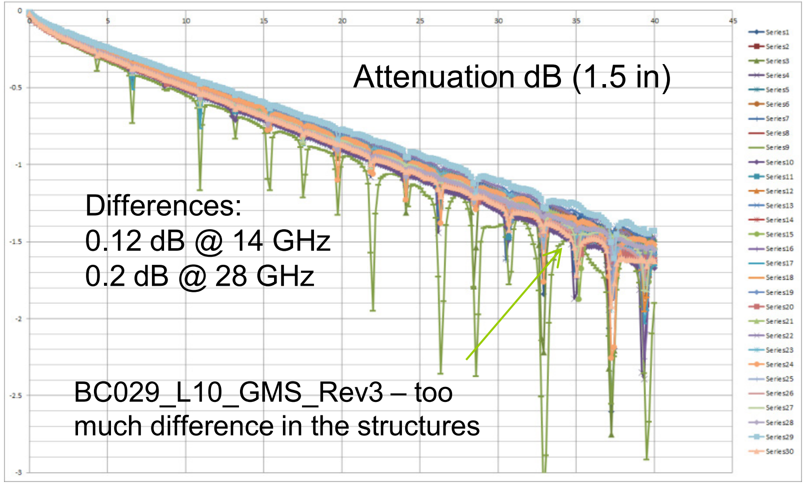
Fiber along long line (spread)

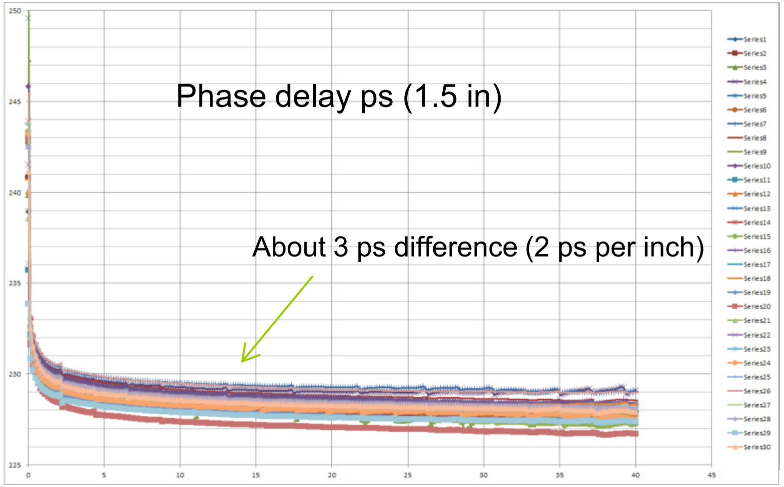
Generalized Modal S-parameters

$$GMT = eigenvals\left(T2 \cdot T1^{-1}\right) = \begin{pmatrix} \exp(-\Gamma \cdot L) & 0 \\ 0 & \exp(\Gamma \cdot L) \end{pmatrix} \Rightarrow GMS = \begin{pmatrix} 0 & \exp(-\Gamma \cdot L) \\ \exp(-\Gamma \cdot L) & 0 \end{pmatrix}$$

T1, T2 - scattering T-matrices of short and long segments

Frequency, GHz





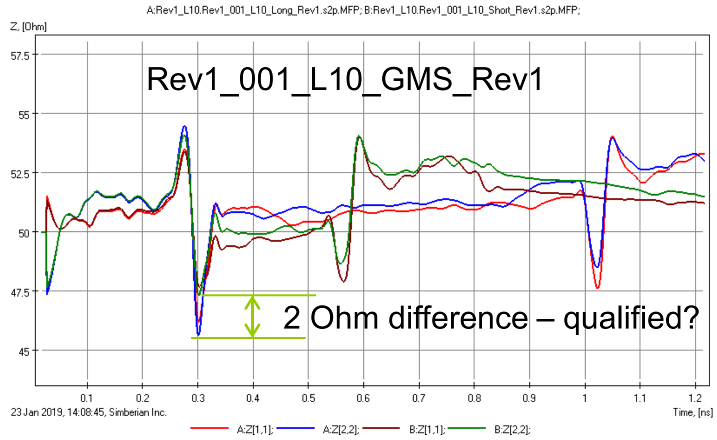
1. BC021_L10_GMS_Rev3
2. BC022_L10_GMS_Rev3
3. BC023_L10_GMS_Rev3
4. BC024_L10_GMS_Rev3
5. BC025_L10_GMS_Rev3
6. BC026_L10_GMS_Rev3
7. BC027_L10_GMS_Rev3
8. BC028_L10_GMS_Rev3
9. BC029_L10_GMS_Rev3
10. BC030_L10_GMS_Rev3
11. BC031_L10_GMS_Rev3
12. BC032_L10_GMS_Rev3
13. BC033_L10_GMS_Rev3
14. BC034_L10_GMS_Rev3
15. BC035_L10_GMS_Rev3
16. BC036_L10_GMS_Rev3
17. BC037_L10_GMS_Rev3
18. BC038_L10_GMS_Rev3
19. BC039_L10_GMS_Rev3
20. BC040_L10_GMS_Rev3
21. BC041_L10_GMS_Rev3
22. BC042_L10_GMS_Rev3
23. BC043_L10_GMS_Rev3
24. BC044_L10_GMS_Rev3
25. BC045_L10_GMS_Rev3
26. BC046_L10_GMS_Rev3
27. BC047_L10_GMS_Rev3
28. BC048_L10_GMS_Rev3
29. BC049_L10_GMS_Rev3
30. BC050_L10_GMS_Rev3

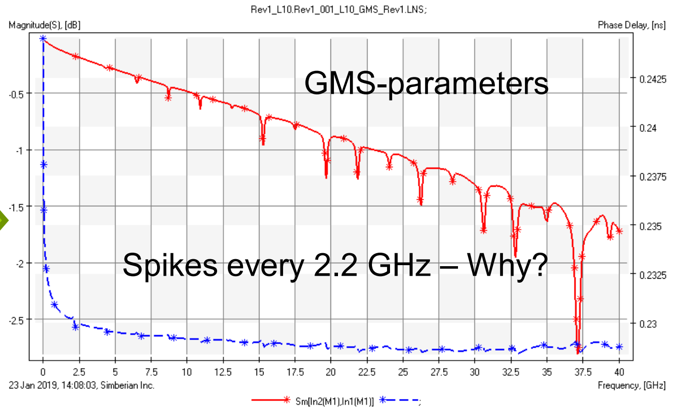
Frequency, GHz

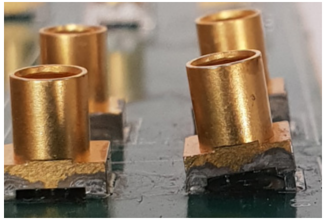
Extracted from 30 pairs up to 40 GHz – too noisy above
Periodic spikes are due to geometry difference in connectors/launches
Can run identification up to 35 GHz and extrapolate by material models

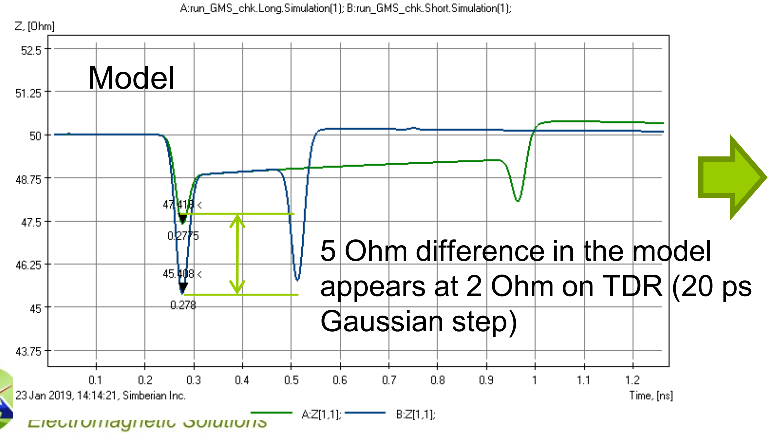
Extracted with Simbeor SDK

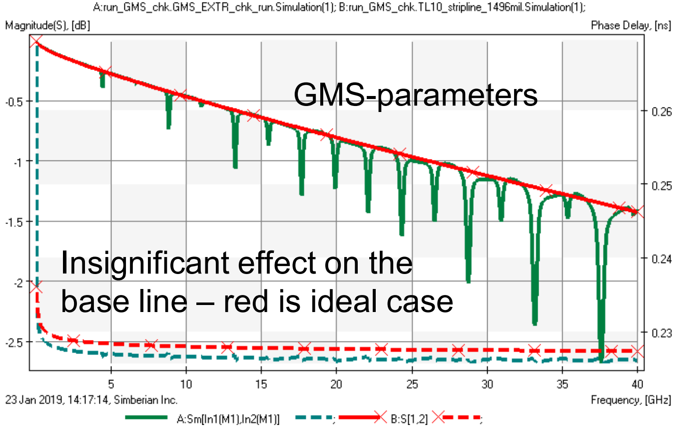
Effect of periodic spikes on GMS-parameters





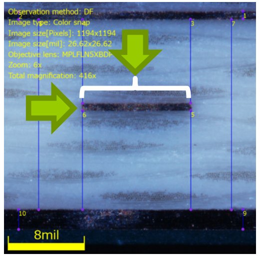


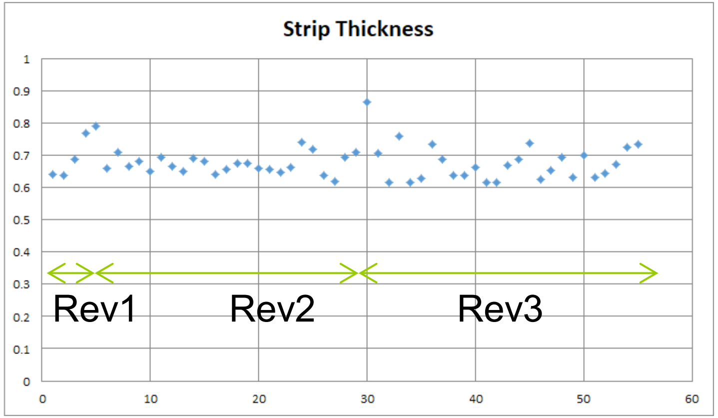


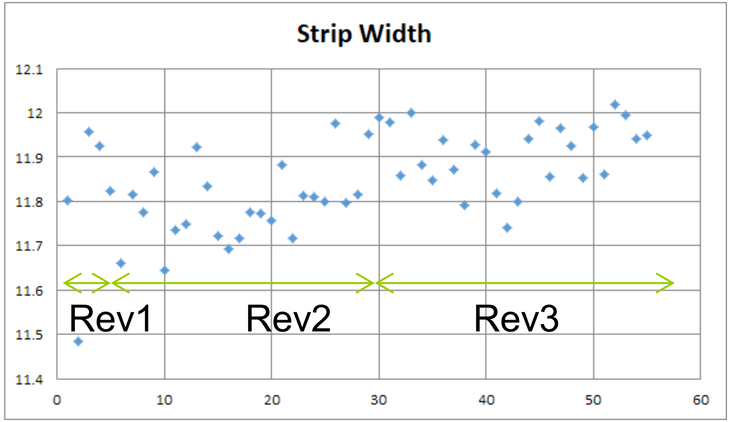


CROSS-SECTIONING AND GEOMETRY VARIATIONS

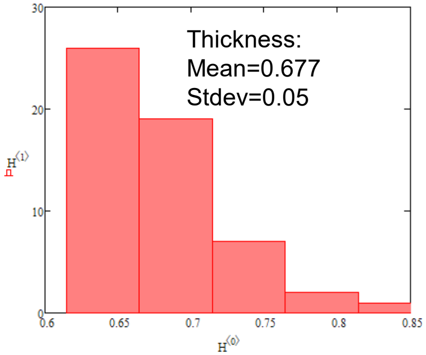
Cross-sectioning – strip geometry

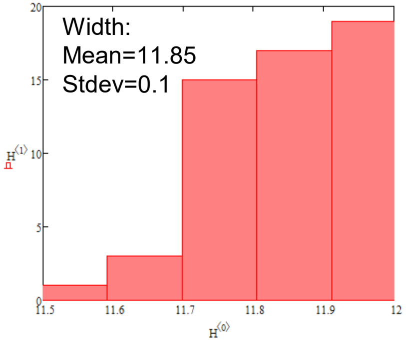




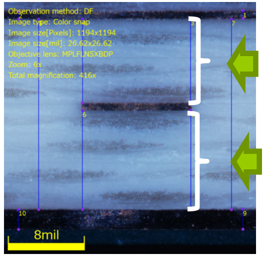


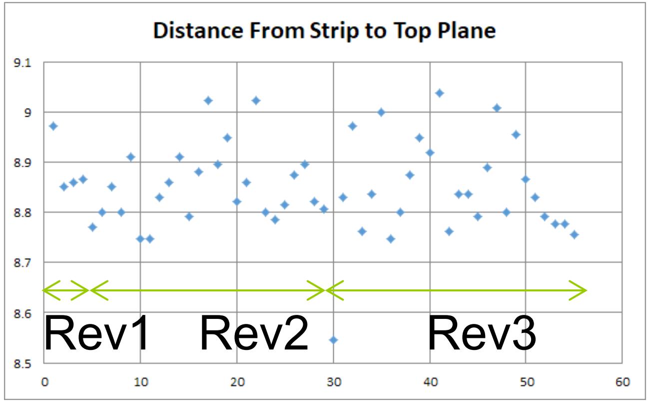
Over 30% variation in the cross-section! It should produce substantial effect on impedance and losses, if we assume that the trace thickness and width are changing along each segment

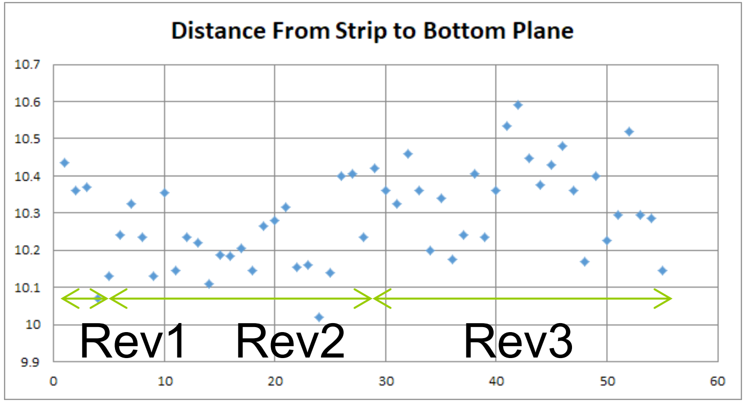




Cross-sectioning- laminate thickness

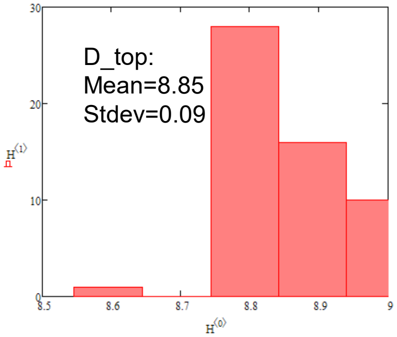


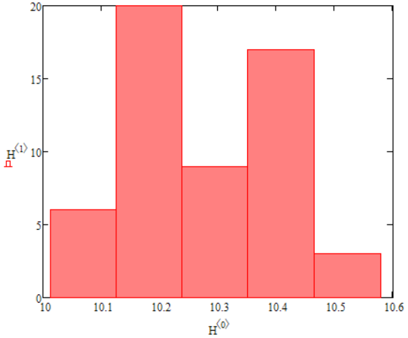




Insignificant variations in the laminate thickness – should not affect the impedance significantly, but still contribute

Should not have effect on losses



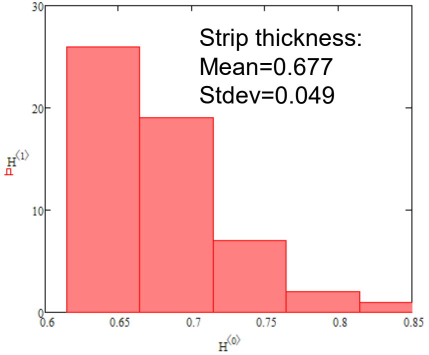


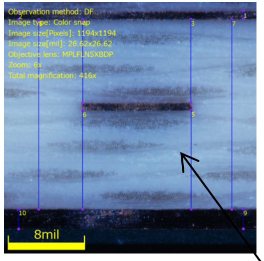
D_bottom:
Mean=10.28
Stdev=0.13

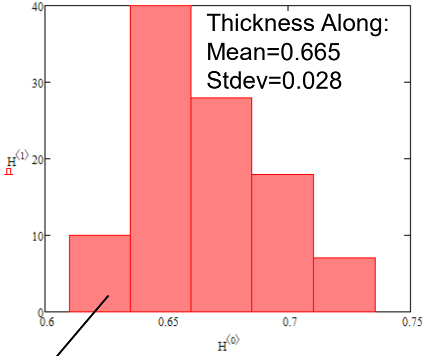
Cross-sectioning summary

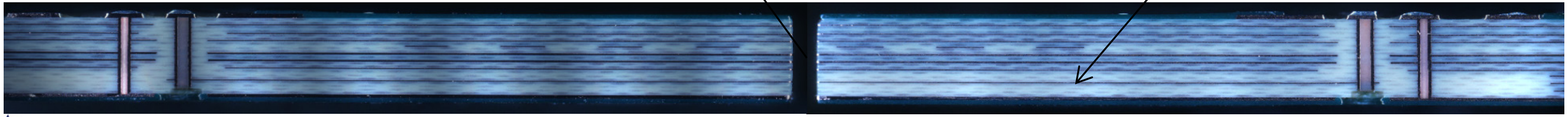
Meas. Value [mil]	Min	Average	Max	Sdt. Dev.
Top Ref. plane thickness	0.658	0.751	0.889	0.069
Strip to top plane distance	8.546	8.845	9.037	0.097
Strip to bot. plane distance	10.146	10.349	10.592	0.112
Strip width	11.74	11.905	12.019	0.074
Strip thickness (batch)	0.614	0.677	0.864	0.049
Strip thickness along one trace	0.61	0.665	0.709	0.028

Additional cross-sectioning along strip (surprise – no explanations from manufacturer)







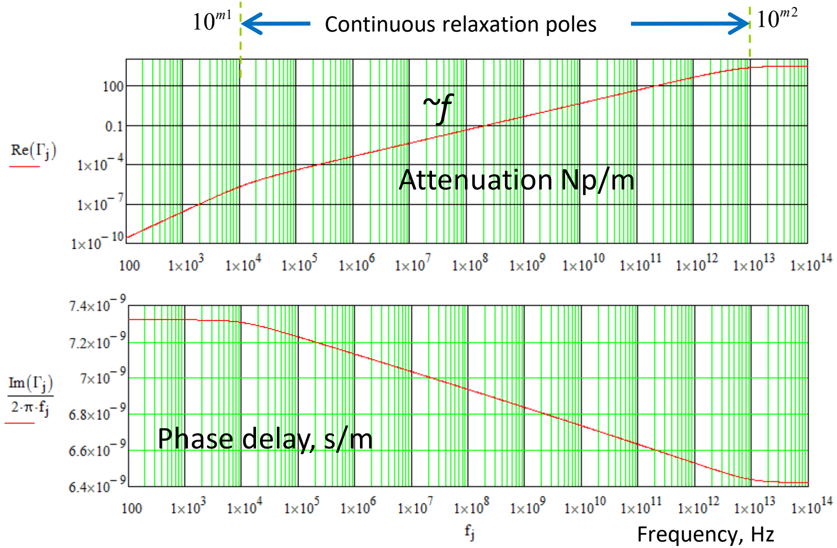


MATERIAL MODELS TO IDENTIFY

Dielectric model to identify – Wideband Debye

Aka Djordjevic-Sarkar or Swensson-Dermer

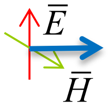
$$\varepsilon_r(f) = \varepsilon_\infty + \sum_{k=1}^{K} \frac{\Delta\varepsilon_k}{1 + i\, f / f_{rk}} \Rightarrow \varepsilon_r(f) = \varepsilon_\infty + \frac{\Delta\varepsilon}{(m_2 - m_1)\cdot \ln(10)} \cdot \ln\left[\frac{10^{m2} + if}{10^{m1} + if}\right]$$



Example:

Plane wave propagation constant

$$\Gamma(f) = i2\pi f \sqrt{\varepsilon_r(f)\cdot \varepsilon_0 \cdot \mu_0}$$

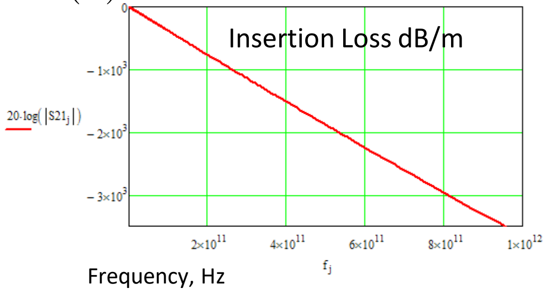


$\varepsilon_\infty = 3.707;\ \Delta\varepsilon = 1.108;\ m1 = 4;\ m2 = 13;$

$\mathrm{Re}\left(\varepsilon(10^9)\right) = 4.2;\ \tan\delta\left(10^9\right) = 0.02$

Generalized transmission parameter for distance *l*:

$$S21(\omega) = e^{-\Gamma\cdot l}$$



This model can be defined with Dk and LT measured at 1 frequency point!

Other wideband model options: Havriliak-Negami

Conductor roughness model to identify: Huray-Bracken

J. E. Bracken, A Causal Huray Model for Surface Roughness, DesignCon 2012

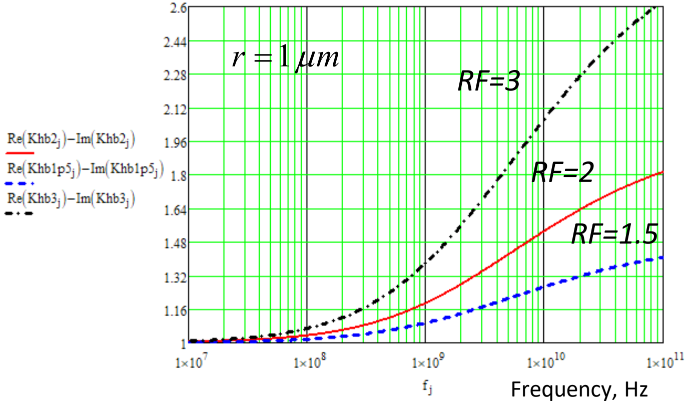
$$K_{sr} = 1 + \sum_k \left((RF_k - 1) \cdot \left(1 + (1-i)\frac{\delta_s}{2r_i} \right)^{-1} \right) \qquad \delta_s = (\pi \cdot f \cdot \mu \cdot \sigma)^{-1/2}$$

Makes SIBC causal! $Z_{rough} = \frac{K_{sr}}{\sigma \cdot \delta_s} \cdot (1+i)$

RFi - roughness factor, defines maximal growth of losses due to all balls with radius ri;
ri – ball radius (SRi parameter in Simbeor);

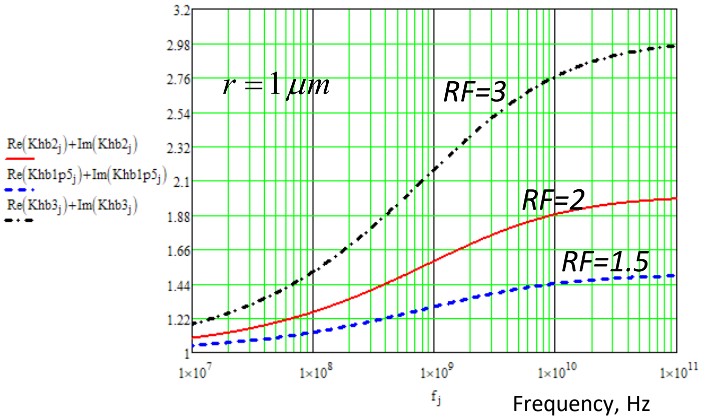
Conductor losses (same as in Huray model)

$$\mathrm{Re}(Z_{rough}) = \left[\mathrm{Re}(K_{sr}) - \mathrm{Im}(K_{sr}) \right] \cdot \frac{1}{\sigma \cdot \delta_s}$$



Additional conductor inductance

$$\mathrm{Im}(Z_{rough}) = \left[\mathrm{Re}(K_{sr}) + \mathrm{Im}(K_{sr}) \right] \cdot \frac{1}{\sigma \cdot \delta_s}$$

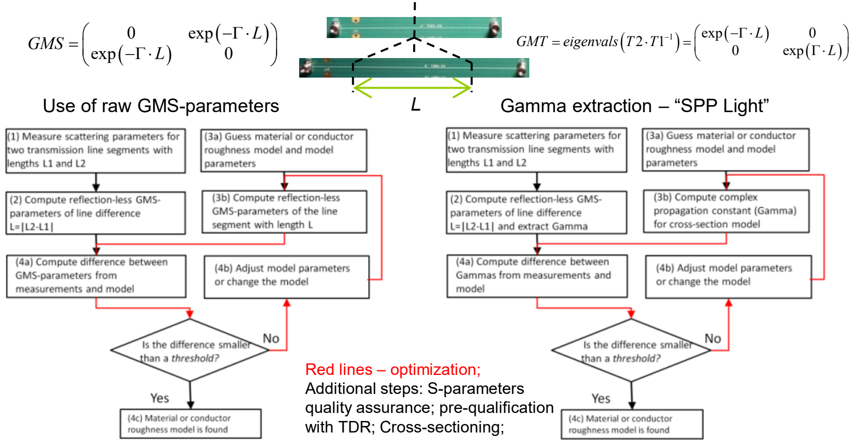


One-level model with just 2 parameters (SR and RF) is used

MATERIAL MODELS IDENTIFICATION & RESULTS

Material model identification

1. Create strip line segment model with dimensions from cross-sections (or mean values) with dielectric and conductor roughness models with preliminary parameters;
2. Identify copper resistivity (RR) by matching measured and computed GMS insertion loss at the lowest frequency (from 10 to 20 MHz);
3. Identify dielectric constant (Dk @ 1 GHz) by matching measured and computed GMS phase delay (from 1 to 40 GHz);
4. Identify loss tangent (LT @ 1 GHz) by matching measured and computed GMS insertion loss at lower frequencies (from 0.05 to 1-2 GHz);
5. Identify conductor roughness model parameters (SR and RF) by matching GMS insertion loss at higher frequencies (from 2 to 25-35 GHz);
6. Adjust dielectric constant (Dk @ 1 GHz) by matching measured and computed GMS phase delay (from 1 to 40 GHz);



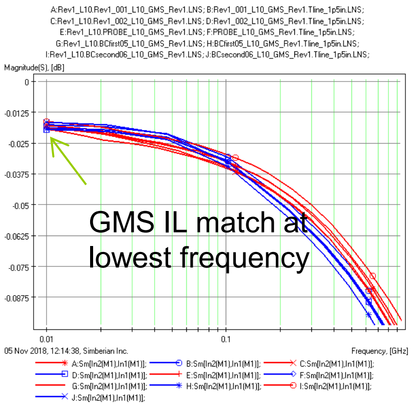
Y. Shlepnev, Broadband material model identification with GMS-parameters, EPEPS 2015.
Y. Shlepnev, Y. Choi, C. Cheng, Y. Damgaci, Drawbacks and Possible Improvements of Short Pulse Propagation Technique, EPEPS 2016.

Implemented in Simbeor SDK (with API for scripting C/C++, Matlab or Python)

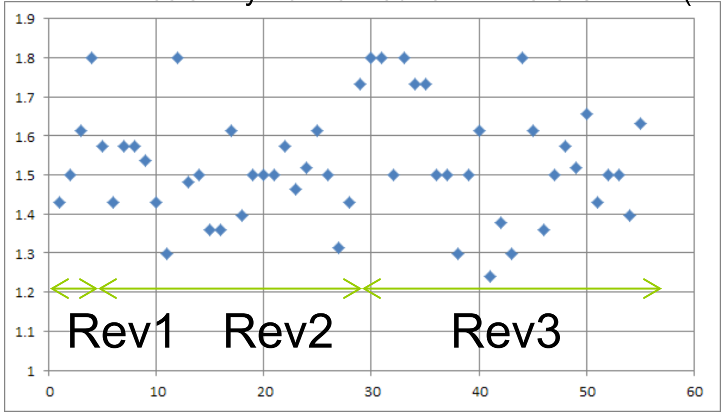
It did not work properly due to the extremely low losses in dielectric…

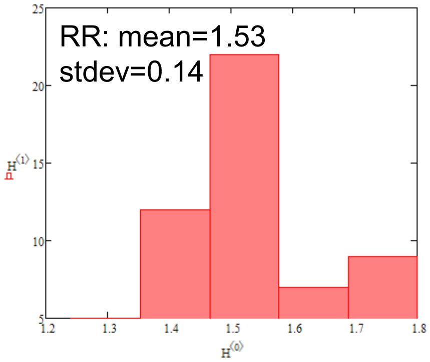
Copper resistivity identification uncertainty

Large variation of the identified relative resistivity – “effective resistivity”
Correlate with the distribution of geometry – 30% variation in strip cross-section cause about 30% variation in the “effective resistivity”



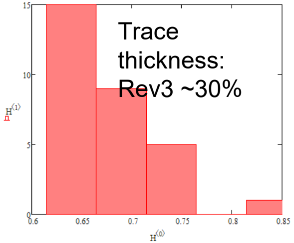
Resistivity normalized to 1.724e-8 Ohm*m (RR)

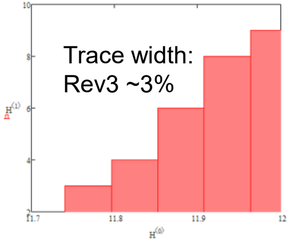




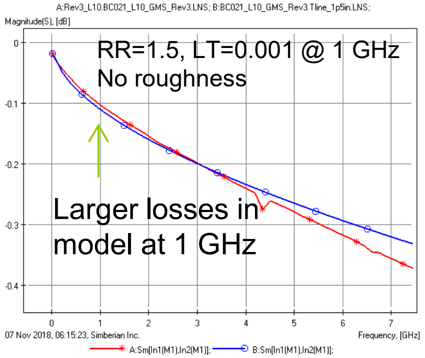
Extracted with Simbeor SDK

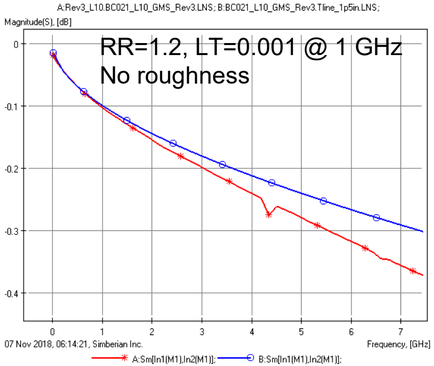
Use minimal value RR=1.2 or average RR=1.5?
Changes in RR can cause variations of losses at lower frequencies that affect the identification of the loss tangent

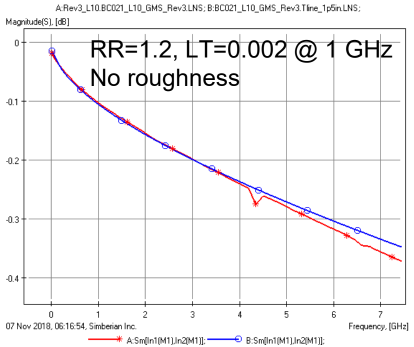




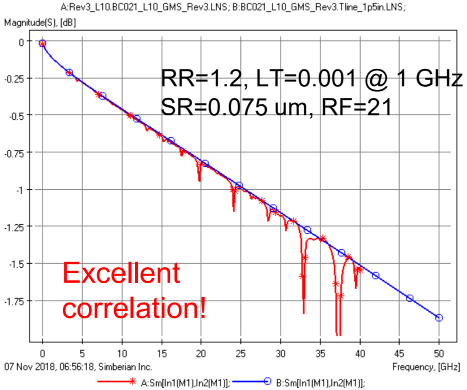
Dielectric and conductor loss separation

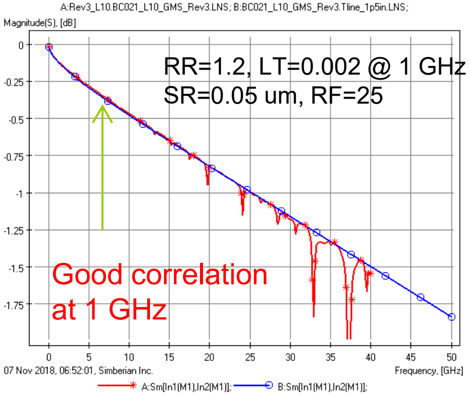






With the identified roughness model





Relative resistivity RR=1.5 produces larger than expected losses at 1 GHz even with LT=0.001
It reflects variations in strip thickness and width
RR=1.2 looks more reasonable to have correlation at lower frequency, but it cannot be confirmed with the measurements
Loss tangent from 0.001 to 0.002 seems possible – it leaves an uncertainty in the loss separation…

Modified identification algorithm

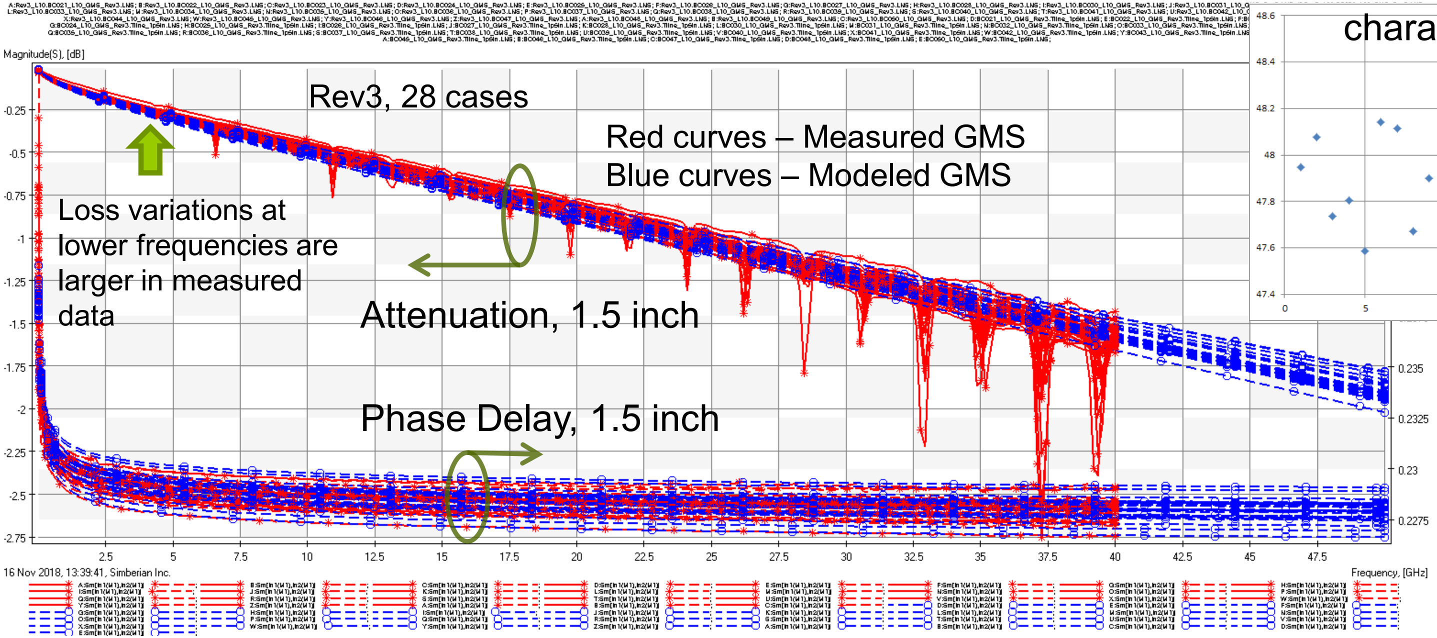
- • *Fix all cross-section parameters to batch mean values;*
- • *Identify Dk @ 1 GHz first by matching GMS phase delay from 2 to 40 GHz;*
- • *Identify relative resistivity (RR) with loss tangent LT @ 1 GHz simultaneously by matching GMS attenuation from 0.01 to 2 GHz;*
- • *Identify roughness model parameters SR and RF by matching GMS attenuation from 2 to 25-35 GHz;*
- • *Correct Dk @ 1 GHz by matching GMS phase delay from 2 to 40 GHz;*

	Min	**Average**	**Max**	**Std. Dev.**
Relative Resistivity, RR	1.12	1.36	1.8	0.2
Surface Roughness, SR [um]	0.13	0.146	0.23	0.023
Roughness Factor, RF	6.2	8.8	9.9	0.8
Dk @ 1 GHz	3.15	3.187	3.22	0.016
LT @ 1 GHz	0.0005	0.0011	0.002	2.7e-4

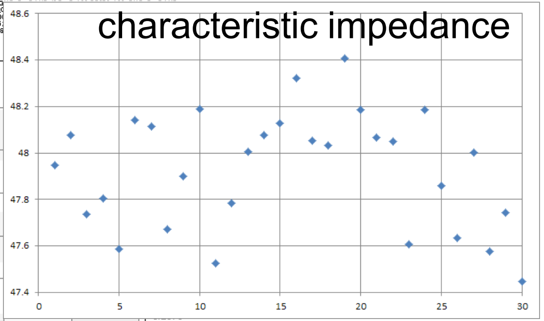
Automated with Simbeor SDK

Fixed cross-section and simultaneous identification of RR and LT (Rev3)

LT and RR are adjusted simultaneously, Dk, SR and RF are adjusted



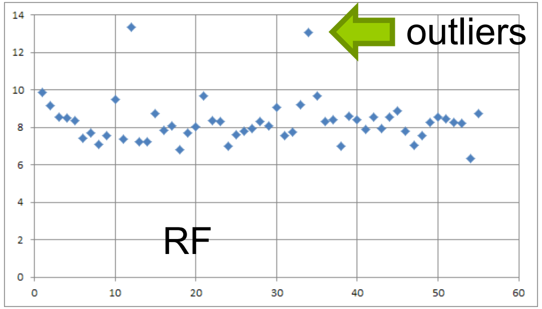
About 1 Ohm variation in characteristic impedance

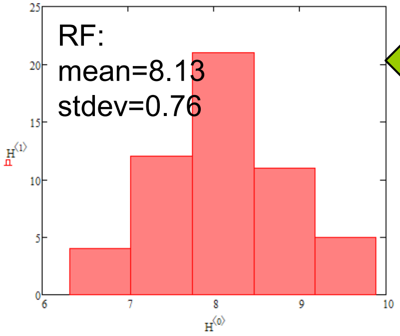


This model is acceptable, but still too complicated for practical use

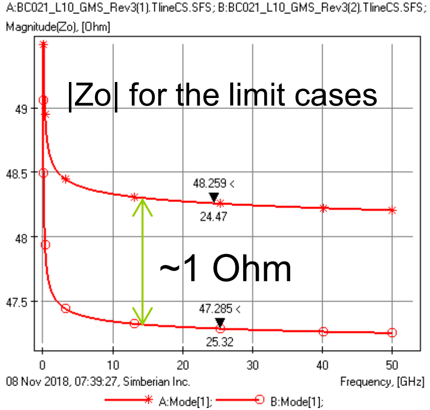
Simplified statistical model
Fixed: Tst=0.677, Wst=11.85, LT=0.001, RR=1.5, SR=0.15 um

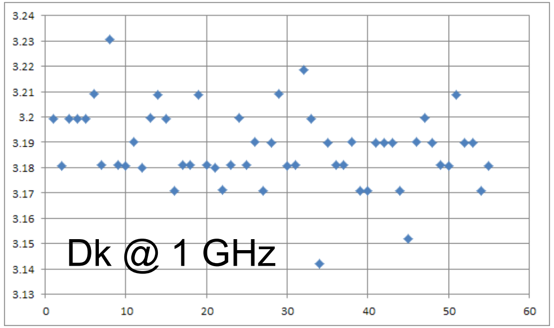
Relative Resistivity – RR=1.5, Roughness – SR=0.15 um, RF is adjusted
Wideband Debye model for dielectric – LT=0.001 @ 1 GHz, Dk is adjusted
Huray-Bracken model for roughness

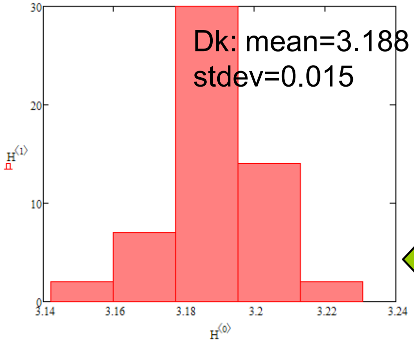




All conductor losses and some impedance variations are included in this parameter





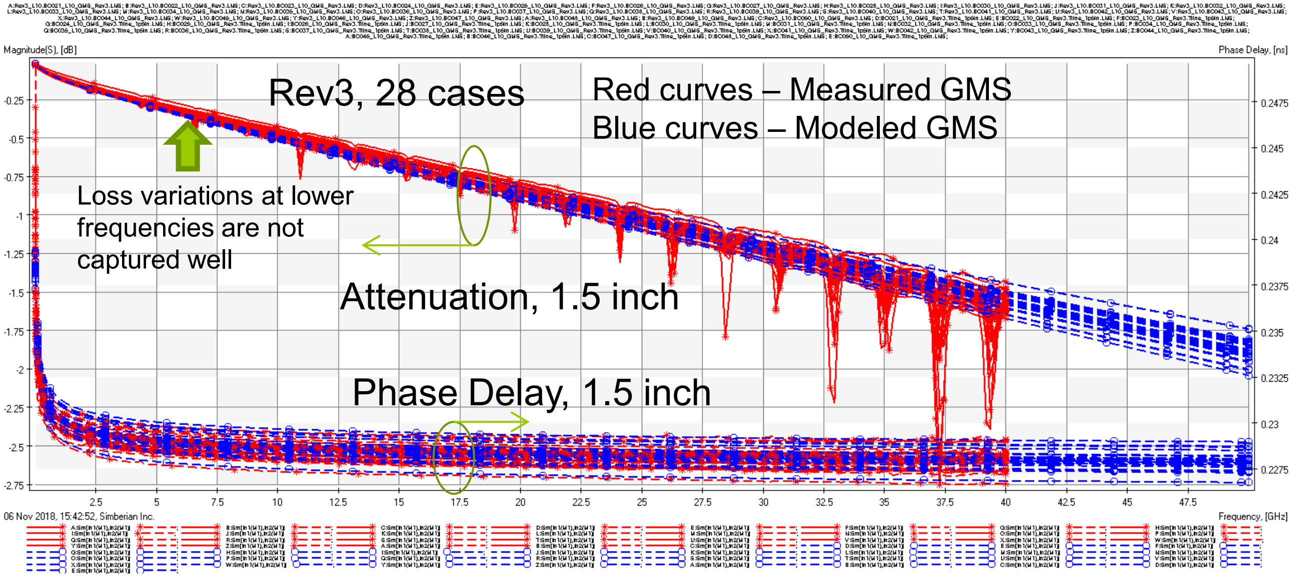


All phase delay variations and some impedance variations are included in this parameter

Simplified model and fixed trace thickness and width (Rev3)

LT=0.001 @ 1 GHz, RR=1.5, SR=0.15 um, Dk, and RF are adjusted

The model quality at lower frequencies can be further improved by taking into account the actual strip geometry variations



Simplified model with fixed cross-section works reasonably good

Conclusion

- This is the first step toward building statistical models for the design of predictable interconnects for 56 Gbps PAM4 signals
- Multiple scenarios of the material model parameters identification with statistical variations are explored
- Trace geometry and roughness causes most of the loss variations in this extremely low loss dielectric case
- Relatively small variations in identified dielectric constant and loss tangent
- In the simplest model, variations in interconnect impedance, losses and dispersion are reduced to just two model variables with acceptable accuracy